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ASSESSMENT OF DIFFERENT DISTRIBUTED GENERATION TECHNOLOGIES FOR A VIRTUAL POWER PLANT

Juliana Zapata Riveros, juliana.zapata@mech.kuleuven.be
Jeroen Vandewalle, jeroen.vandewalle@mech.kuleuven.be
William D'haeseleer, william.dhaeseleer@mech.kuleuven.be
University of Leuven (KU Leuven) Energy Institute – branch Applied Mechanics and Energy Conversion (TME), Celestijnenlaan 300A P.O Box 2421, B-3001 Heverlee, Belgium
Phone: +32 16 32 25 11
Energyville (joint venture of VITO NV and KULeuven), Dennenstraat 7, 3600 Genk

ABSTRACT

Appropriately designed distributed generation technologies can help to reduce transmission and distribution losses. This can be achieved by promoting the local use of the electricity generated. Additionally, it is expected that due to their low generation capacity several distributed generation technologies will be grouped in a virtual power plant (VPP) to act together in the market.

This paper presents a closer look at the cooperation of photovoltaic (PV) and micro-cogeneration (CHP) facilities within a VPP and compares to the case of independent generation. The results show that micro-CHP and PV are complementary technologies and that working together leads to an increase in the self-consumption of electricity leading to economic operational benefits.

Keywords: Distributed generation, local consumption, Virtual power plant, cogeneration, photovoltaic.

Nomenclature

C_{CHP}	Operational cost of CHP	€
C_{boiler}	Operational cost of Boiler	€
C_{grid}	Grid cost	€
G_{self}	Avoided cost of buying electricity	€
G_{grid}	Revenue for feed electricity into the grid	€
P_{local}	Local price of electricity	€/kWh
P_{spot}	Feed-in tariff	€/kWh
P_{ng}	Fuel price	€/kWh
$\dot{Q}_{demand}$	Heat demand	kW
$\dot{E}_{demand}$	Electric demand	kW
$\dot{E}_{house1}$	Electric demand of the first house	kW
$\dot{E}_{house2}$	Electric demand of the second house	kW
$\dot{Q}_{chp}$	Thermal power CHP unit	kW
$\dot{Q}_{boiler}$	Thermal power condensing boiler	kW
$\dot{Q}_{c}$	Thermal (dis)charging power	kW
$\dot{Q}_{prim}$	Primary energy	kW
Q_{st}	State of charge of the storage tank	kWh
α_E	Electrical efficiency of the CHP	%
α_Q	Thermal efficiency of the CHP	%

η_{st}	Efficiency of the storage tank	%
η_{boiler}	Efficiency of the auxiliary boiler	%
Δt	Time interval	h
$\dot{E}_{chp}$	Electric power CHP	kW
$\dot{E}_{local}$	Electric power consumed locally	kW
$\dot{E}_{local\_PV}$	PV Electric power consumed locally	Kw
$\dot{E}_{local\_chp}$	CHP Electric power consumed locally	kW
$\dot{E}_{grid}$	Electric power fed into the grid	kW
$\dot{E}_{grid\_PV}$	PV Electric power fed into the grid	kW
$\dot{E}_{grid\_chp}$	CHP Electric power fed into the grid	kW
Q_{st_max}	Maximum storage capacity	kWh
$\dot{Q}_{boiler\_max}$	Maximum boiler output	kW
$\dot{Q}_{chp\_max}$	Maximum CHP thermal power	kW
$\dot{E}_{chp\_max}$	Maximum CHP electric power	kW
$\dot{Q}_{chp\_min}$	Minimum CHP thermal power	kW
$\dot{E}_{chp\_min}$	Minimum CHP electric power	kW
RP	Relative price	-
P_r	Profitable price	€/kWh

1. INTRODUCTION

The massive penetration of distributed generation technologies (DG) has inherent advantages that have been largely discussed. According to [1] there are presently several drivers that will contribute to promote the penetration of DG. The most remarkable are: concerns for reliability and quality of supply; the liberalization of the electricity market; environmental concerns and the savings on the transmission and distribution cost.

Regarding the last aspect it has been reported that transmission losses account in average for about 7% in OECD countries in the year 2002 [2]. In Belgium, for instance, it was reported in 2009 that transmission losses summed up to 5.4% of the total production [3]. Furthermore, it has been estimated that eliminating these losses and part of the distribution losses, would result in a cost saving of around 10 % of the electricity cost[1].[1]

In countries such as Germany, new policies are promoting self-consumption of electricity starting from the most characteristic DG technology: Photovoltaic installations (PV). The new regulation

[1] Note that DG can avoid a substantial part of the transmission losses (being mainly Ohmic losses), but only a small part of the distribution losses (if the DG is grid connected). Since DG facilities like to use the distribution grid to either sell or by electricity, they are co-responsible for its proper functioning. Most of the losses in distribution grids are the magnetic losses in transformers, which are only weakly dependent on the loading of the grid.

defines self- consumption as: the possibility of an electricity consumer to connect a PV system with a capacity that corresponds to his consumption for on-site consumption and feed the non-consumed electricity into the grid [4]. According to this definition, the electricity might be consumed not only on-site but also near the site making use of the existing distribution grid.

If the right conditions are met, self-consumption may help to reduce the burdens that DG imposes on the electricity grid and it can increase the interest of private investors for small generation. Thus, it helps to expand DG technologies, if properly designed.

Due to the characteristically low generation capacity of DG, it is expected that different types of generators (e.g. wind, solar, cogeneration) and storage devices will be aggregated in what is known as a Virtual Power Plant (VPP) in order to improve the combined characteristics and to compete on the wholesale market. Thus a VPP will be an entity that controls several decentralized units and will appear on the market as one compact power plant.

Controlling different technologies imposes a challenge to the VPP. Nevertheless, a good control strategy will help to counterbalance the weakness of one technology (e.g. intermittent output) using the strengths of another one. Some studies have already been performed involving CHP and wind [5] to overcome the variability of the wind output.

With respect to PV and CHP, [6] proposes the use of both technologies in order to reduce the reverse power flow from the PV installations. Similarly in [7] it is stated that the penetration of PV in the United States (US) can be expanded making use of hybrid systems (PV and CHP with heat storage); these systems will help to overcome the inherent intermittency of the PV installations. In the same way, [8] reports the installation of a hybrid system of biomass cogeneration and solar PV in a hotel in Portugal.

In this paper, a closer look to the cooperation between solar PV and CHP is given, an optimization algorithm is employed to decide the optimal control strategy of the CHP and several aspects such as the self-consumption rate and the economic advantages are analyzed. The second section gives an overview of the methodology applied and explains in detail the optimization algorithm used. Section 3 describes the assumptions employed during this work. Afterwards, in section 4, a complete analysis of the results is presented. Finally, conclusions are stated.

2. METHODOLOGY

In the framework of the present study, the heat and electricity consumption of two different multi-family houses are considered.[2] The first house corresponds to a 3-family-house with an annual electric consumption of 11.9 MWh/year (Thermal consumption =120.3 MWh/year). It generates heat and electricity by means of a micro-CHP system consisting of a cogeneration device, an auxiliary burner and a heat storage tank. The micro-CHP system employs natural gas as fuel.

The second house has an annual electric consumption of 4.2MWh/year. It generates electricity making use of PV panels. Since there is no heat-grid interconnection, the heat consumption or demand of the second house is irrelevant for the present study. Nevertheless the heat consumption of the first house is met at all time and dumping heat is not allowed.

Three different scenarios are analyzed. In the reference scenario (NO VPP) both dwellings produce their electricity independently. A generation surplus or an additional demand of electricity can at any time be balanced by the grid. In the second and third scenarios it is assumed that both houses are part of a VPP, as shown in Figure 1**,** and thus cooperate in order

[2] In the context of self-production of heat and electricity, a distinction between “consumption” and “demand” is appropriate. By “consumption” all end use of energy is meant, whereas “demand” is the amount bought or obtained from the grid or from the VPP.

to meet their total electricity consumption. The major difference between the scenarios 2 and 3 is the amount of PV electricity generated. In the second scenario (50% PV) the PV installation generates 50% of the total annual electric consumption of the house, whereas in the third scenario (100% PV) it produces 100% of its annually integrated consumption.

The price to buy electricity from the grid, also known as local price (P_{local}), and the feed-in tariff (P_{spot}) are the same for all scenarios. However, the feed-in tariff is most of the time lower than the buying price in order to promote local or self-consumption and thus reduce transmission losses and the stress on the grid. The distribution of the profits between the VPP and the prosumers is not a topic of this work.

Additionally, the model evaluates the three scenarios considering of two different commercial micro-CHP devices for the first house: two internal combustion engines (ICE) one with on/off regulation and a capacity of 5.5 kW_e and a second machine able to modulate between the range of 1.2 - 4.7 kW_e.[3]

The simulations employ a Mixed Integer Linear mode that is solved by CPLEX. This algorithm decides on the most economic schedule for the operation of the micro-CHP, auxiliary boiler and heat storage. The model is programmed in the commercial software GAMS using an interface with MATLAB to perform further analysis of the data. The influence of the heat storage capacity and electricity price change is studied. Furthermore, the economic benefits are compared and calculated for the different scenarios.

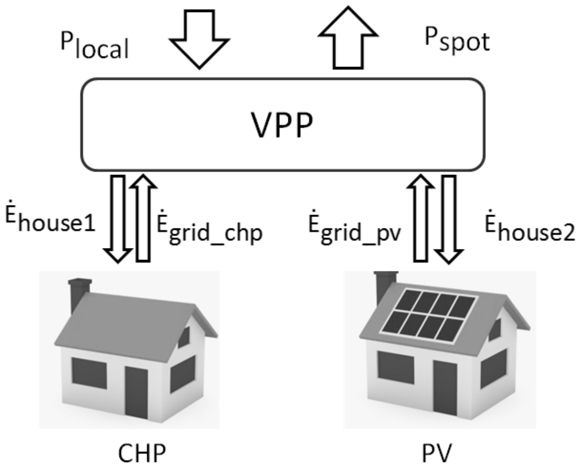

Figure 1: VPP scenario with two different houses. The first house produces heat and electricity with a CHP device; the second house makes use of PV installation; both houses cooperate to meet common electricity consumption. The VPP entity makes interface with the electricity market

[3] The thermal power of both units is specified below.

2.1. Optimization algorithm

The objective of the optimization algorithm is to find an operational schedule for the CHP and boiler that minimizes the energy cost. This cost is estimated as the sum of the operational cost of the CHP (C_{CHP}) and boiler (C_{boiler}) minus the savings achieved by the local use of the electricity generated (G_{Self}) and the revenues obtained by feeding the remaining electricity to the grid (G_{grid}). This is expressed in Equation (1) in its most classic form and in Equation (2) in an expanded form:

$$min = \sum_{t=1}^{T} \left(C_{CHP}(t) + C_{boiler}(t) - G_{self}(t) - G_{grid}(t) \right) \tag{1}$$

The operational cost of the CHP and boiler are calculated as the amount of fuel use per fuel price (P_{ng}). The amount of fuel needed for each device, can be estimated using the total heat generated by the machine during a time interval ($\dot{Q}_{chp}$ and $\dot{Q}_{boiler}$) over the respective thermal efficiency of each machine (α_Q and η_{boiler}). The profits are equal to the amount of electricity used locally ($\dot{E}_{local\_chp}$) or sent to the grid ($\dot{E}_{grid\_chp}$) per the local (P_{local}) or spot price (P_{spot}) respectively:

$$min = \sum_{t=1}^{T} \left(\left(\frac{\dot{Q}_{chp}(t)}{\alpha_Q} + \frac{\dot{Q}_{boiler}(t)}{\eta_{boiler}} \right) \cdot P_{ng}(t) - \dot{E}_{local\_chp}(t) \cdot P_{local}(t) - \dot{E}_{grid\_chp}(t) \cdot P_{spot}(t) \right) \tag{2}$$

Additionally, the optimization algorithm should guarantee that the demand for heat ($\dot{Q}_{demand}$) will always be met using the CHP, the boiler or the heat stored in the buffer. This is described in Equation (3). The variable $\dot{Q}_C$ represents the thermal (dis)charge power of the storage. It can take positive or negative values depending on whether the storage is being discharged or charged during the time interval respectively.

$$\dot{Q}_{demand}(t) = \dot{Q}_{chp}(t) + \dot{Q}_{boiler}(t) + \dot{Q}_c(t) \tag{3}$$

The state of charge (i.e., the thermal energy content) of the storage tank (Q_{st}) is calculated using Equation (4). The efficiency of the storage tank is assumed to be constant (η_{st}). As the time step is always one hour it is not written explicitly in the equations:

$$Q_{st}(t) = (1 - \eta_{st}) * Q_{st}(t-1) - \dot{Q}_c \tag{4}$$

On the other hand, the electricity generated by the CHP ($\dot{E}_{CHP}$) can be used for self-consumption ($\dot{E}_{local\_chp}$) or fed back in to the electricity grid ($\dot{E}_{grid}$); see Equation (5). The feed-in tariff is most of the time lower than the local buying tariff, as further elaborated in section 3.3.

$$\dot{E}_{CHP}(t) = \dot{E}_{local\_chp}(t) + \dot{E}_{grid\_chp}(t) \tag{5}$$

In the 'NO VPP 'scenario the self-consumption cannot be higher than the electric demand of the first house ($\dot{E}_{house1}$). On the other hand, in the scenarios with VPP, self-consumption should be limited to the common electric demand of both houses minus the amount of PV electricity that can be used locally (E_{local_PV}) this is expressed in Equation (6). In this equation if E_{local_chp} is smaller than the local demand (right term of the equation), additional electricity has to be imported from the grid to meet the local electric demand.

$$\dot{E}_{local\_chp}(t) \leq \dot{E}_{house_1}(t) + \dot{E}_{house_2}(t) - \dot{E}_{local\_PV} \quad (6)$$

Furthermore, the optimization algorithm is constrained by technical restrictions that prevent exceeding the operational limits of the machines. This is summarized in Equations (7)-(10):

$$0 < Q_{st}(t) < Q_{st\_max} \quad (7)$$

$$0 < \dot{Q}_{boiler}(t) < \dot{Q}_{boiler\_max} \quad (8)$$

$$\dot{Q}_{chp\_min} < \dot{Q}_{chp}(t) < \dot{Q}_{chp\_max} \quad (9)$$

$$\dot{E}_{chp\_min} < \dot{E}_{chp}(t) < \dot{E}_{chp\_max} \quad (10)$$

It is important to remark that the non-modulating micro-CHP can only work at full load (ON-OFF). This means that $\dot{E}_{chp}$ is either zero ($\dot{E}_{chp\_min}$=0) or $\dot{E}_{chp\_max}$. Conversely, a modulating machine can change its output continuously between a minimum ($\dot{E}_{chp\_min}$≠0) and a maximum ($\dot{E}_{chp\_max}$) value during operation. It only becomes zero when the machine is switched off. Finally, the relationship between primary, thermal and electrical energy is assumed to be linear and will be further explained in section 3.2

3. ASSUMPTIONS

3.1. CHP and boiler size

In order to find a reasonable size for CHP, the maximum rectangle technique described in [9] was employed. The first step to apply this methodology is to sort the heat demand in a descending order to obtain the so called load duration diagram, as illustrated in Figure 2. Afterwards, the biggest rectangle that can be inscribed under the load-duration curve (also known as monotonic curve) should be determined. The intersection between the rectangle and the vertical axes corresponds to the optimal thermal capacity for the micro-CHP device (point A in Figure 2). The remaining heat demand should be covered by an auxiliary boiler.

In this work, the capacity of the thermal storage is going to be expressed in relation to the thermal energy produced by the CHP during one hour. As defined in [10], the term relative storage capacity (RSC) will be employed to denote the ratio between the storage capacity of the buffer and the thermal output of the CHP during one hour time step, as shown in Equation (11):

$$RSC = \frac{Q_{st\_max}}{\dot{Q}_{chp} \cdot \Delta t} \quad (11)$$

As explained in [9] and [10], an optimal thermal buffer should be able to store between two to three times the thermal outputs produced during one hour by the CHP. Thus, in this paper an RSC of 2 will be employed unless a different value is specified.

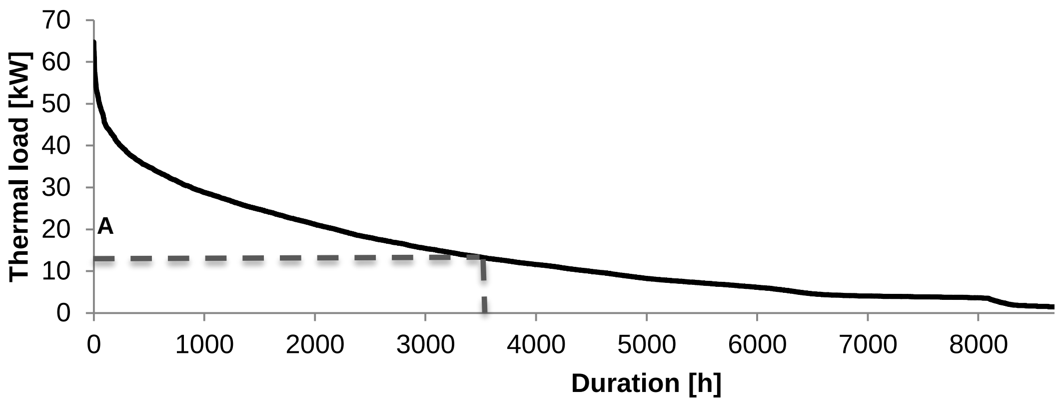

Figure 2: Maximum rectangle method: the largest rectangle (dashed lines) that can be inscribed under the monotonic curve (black) determines the capacity of the CHP (point A)

3.2. Cogeneration devices

As described in section 3.1, the maximum rectangle method was applied to the used profiles in order to find a reasonable size for the CHP device. The result indicates that a CHP with a thermal capacity of 13kW should operate during approximately 3500 hours in house 1. Taking this result into account, two different commercial CHP devices with a rated thermal capacity of approximately 13kW were chosen and modeled. One of these devices is able to work at part load while the other one only has ON-OFF regulation.

The non-modulating device corresponds to the Senertec Dachs micro-CHP. The Senertec unit is based on an internal combustion engine fed from a single fuel source such as natural gas or LPG. The characteristics of this machine are summarized in Table 1. The total Fuel utilization ratio (F.U.R)[4] is 88%.

Table 1: Rated technical characteristics SENERTEC [11]

	UNIT	VALUE
$\dot{Q}$ fuel	kW	20.5
$\dot{Q}$ thermal	kW	12.5
$\dot{Q}$ electrical	kW	5.5
F.U.R	%	87.8

The second machine is the Ecopower Plus micro-CHP, which is a gas driven engine that enables full modulation between 1.2 kWe and 4.7 kWe (3.8 to 12.5 kWth). Figure 3 illustrates the steady state characteristics of the Ecopower Plus micro-CHP as measured in [11].

The device exhibits almost linear relationships between the electric and thermal output, as well as between the electric output and the fuel use. These relationships are described in Equations (12) and (13).

$$\dot{Q}_{prim} = 3.87 \cdot \dot{E}_{chp} + 0.79 \quad (12)$$

$$\dot{Q}_{chp} = 2.54 \cdot \dot{E}_{chp} + 0.68 \quad (13)$$

[4] The fuel utilization ratio is defined as the ratio of the total quantity of useful power generated by the cogeneration unit and the required fuel.

As the simulations are performed in an hourly time step, the dynamic characteristics of the unit are not taken into account.

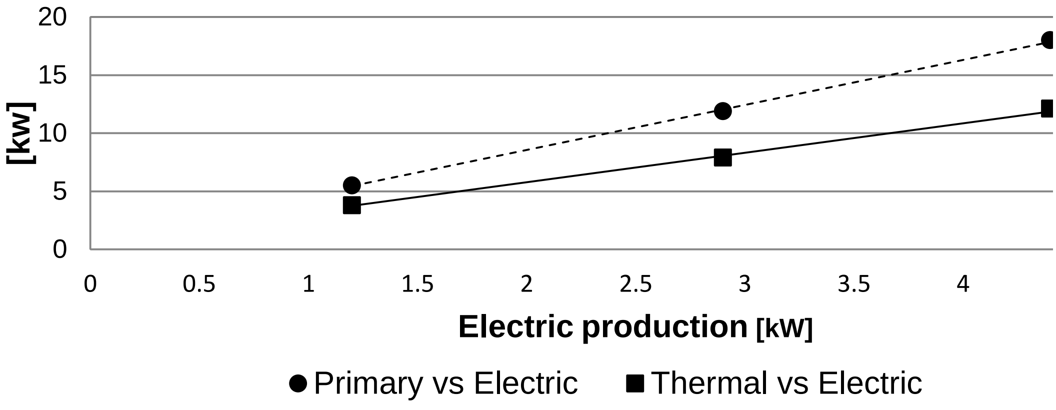

Figure 3: Technical characteristics of the Micro-CHP Ecopower Plus. The figure shows the linear relationship between electric and primary energy (dashed line) and the electric and thermal energy (full line).

3.3. Gas and electricity prices

For the present work the gas price is assumed to be constant and equal to 0.06 €/kWh. On the other hand, it has been assumed that the price to buy electricity from the grid is equal to 0.15 €/kWh at night and 0.22€/kWh during the day. This price will change as a function of the gas price in section 4.2. Finally, the feed-in tariff used for the calculations corresponds to the spot market price in Belgium for the year 2007, which had an average value of 0.039 €/kWh during the night and 0.053€/kWh in the day [12].

3.4. PV profile

The PV profile used was measured at a fixed rooftop PV installation at the KU Leuven. The profile was rescaled for the house to cover 50 and 100% of the annual electricity demand of the dwelling [13].

4. RESULTS

In the following section, the most important outcomes of this research are presented and analyzed. First, the influence of the heat storage capacity on the CHP production is assessed. Then, the effects of the variation of the local price on the CHP production are analyzed and afterwards the changes on the CHP production due to the VPP arrangement are studied (yearly and daily changes). Finally, an economic comparison between the different scenarios is performed. Conclusions are drawn in the next section.

4.1. Influence of the storage capacity on the CHP production.

In order to analyze the influence of the heat storage capacity on the electricity production of the CHP, the RSC was varied continuously from 0 to 5 (0 corresponds to no storage installed). Figure 4 illustrates the consequences of this variation in a non-modulating CHP.

It can be observed that introducing a storage device of 1 RSC leads to a significant increase in the CHP production (around 46% with respect to 0 RSC). On the other hand, the effects of enlarging the storage capacity further than 1 are very moderate and beyond 3 RSC they are negligible. The response of a modulating micro-CHP to a change in the storage capacity is similar to that of the non-modulating one. However, the electricity production increase is less marked (approximately 12% with respect to 0 RSC).

Furthermore, a closer look at the seasonal production is depicted in Figure 5. The graph compares CHP electricity generation between the different seasons using various storage capacities. It is clear that the influence of the storage capacity is more important during summer when the production rises nearly four times with respect to the case when no storage is installed. In contrast, during winter the increase of the storage capacity has only a marginal effect (approximately 8% of increase with respect to the case without storage). This outcome result of the fact that in winter the produced heat can be directly used most of the time due to the large heat demand. Thus, there is no major need to store the heat.

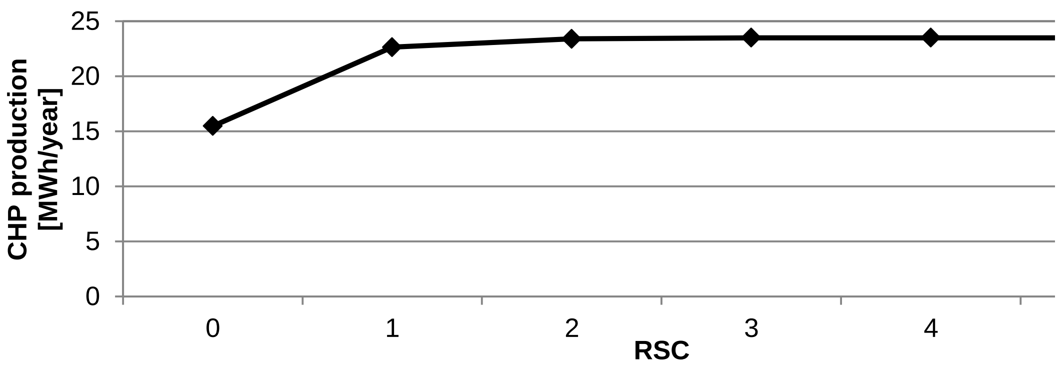

Figure 4: Annual CHP electricity production as a function of the relative storage capacity (RSC). The graph shows how introducing a heat buffer leads to a major increase on the CHP production, but without substantial further increases beyond RSC > 1.

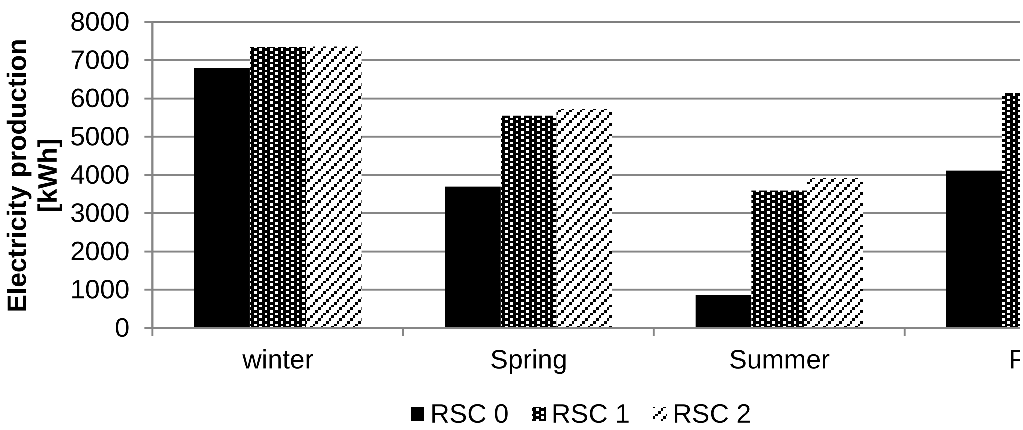

Figure 5: Seasonal electricity production with different relative storage capacities (RSC 0, RSC 1, RSC 2). The largest increase in production is present in summer.

4.2. Impact of the local electricity price on the CHP production

As stated in [14], the cost to produce electricity with the CHP can be estimated[5] as the cost of the primary energy needed to produce the electricity minus the cost of the primary energy needed for the boiler to generate the same amount of heat. As expressed in Equation (14):

$$C_{el} = \frac{\dot{E}_{chp}}{\propto_E} \cdot P_{ng} - \frac{\dot{Q}_{chp}}{\eta_{boiler}} . P_{ng} \tag{14}$$

Consequently, the operation of the CHP is profitable only when the price (Pr) received for the electricity generated ($\dot{E}_{chp}$) is higher than the cost of the production (see Equation (15)).When the condition of Equation (15) is satisfied, Pr can be regarded as a profitable price. If for instance the local price (which equals to the price to buy electricity from the grid) falls below the profitable price, the operation of the CHP is non-desirable and producing heat with the boiler will be preferred.

$$\dot{E}_{chp} \cdot P_r > C_{el} \tag{15}$$

In this particular case, the profitable price for both micro-CHP devices was estimated as: $1.2 \cdot P_{ng}$ for the Senertec and around $1 \cdot P_{ng}$ for the Ecopower (The value changes from $1.05 \cdot P_{ng}$ to $1.07 \cdot P_{ng}$ depending on the electric output) assuming a boiler efficiency of 90%. As the profitable price is expressed as a function of the fuel price, a new term, the relative electricity price (RP), is introduced that will help to relate the local electricity price in terms of the gas price. Thus, the relative price denotes the ratio between these two magnitudes as shown in (16):

$$RP = \frac{P_{local}}{P_{ng}} \tag{16}$$

Subsequently, in order to evaluate the influence of the local electricity price on the operation of the micro CHP, the simulations were performed changing the relative price from 0.5 to 4 (i.e. the electricity price was varied from $0.5 \cdot P_{ng}$ to $4 \cdot P_{ng}$). The spot price is the same for all the simulations and as mentioned in section 3.3 equal to the spot market price in Belgium for the year 2007 .The results are illustrated in Figure 6.

In Figure 6, the dashed line corresponds to the total electricity production of the CHP during one year. Before the relative price reaches the value of 1 ($P_{E\_local}<P_r$), the CHP is in operation only when the spot price is higher than the profitable price and thus all the electricity produced is sent to the grid (light shaded areas).

Once the relative price is higher than one ($P_{E\_local}>P_r$), two different situations can be observed: the non-modulating micro-CHP increases its annual electricity production gradually, while on the

[5] Note that this approach gives all advantage of the CHP to the electrical side, since it is assumed that the heat is produced with the same efficiency as in a boiler. Similar approaches giving the advantage to the thermal side exist.

other hand, the modulating micro-CHP raises its electricity production abruptly and no major changes are observed with further price increase.

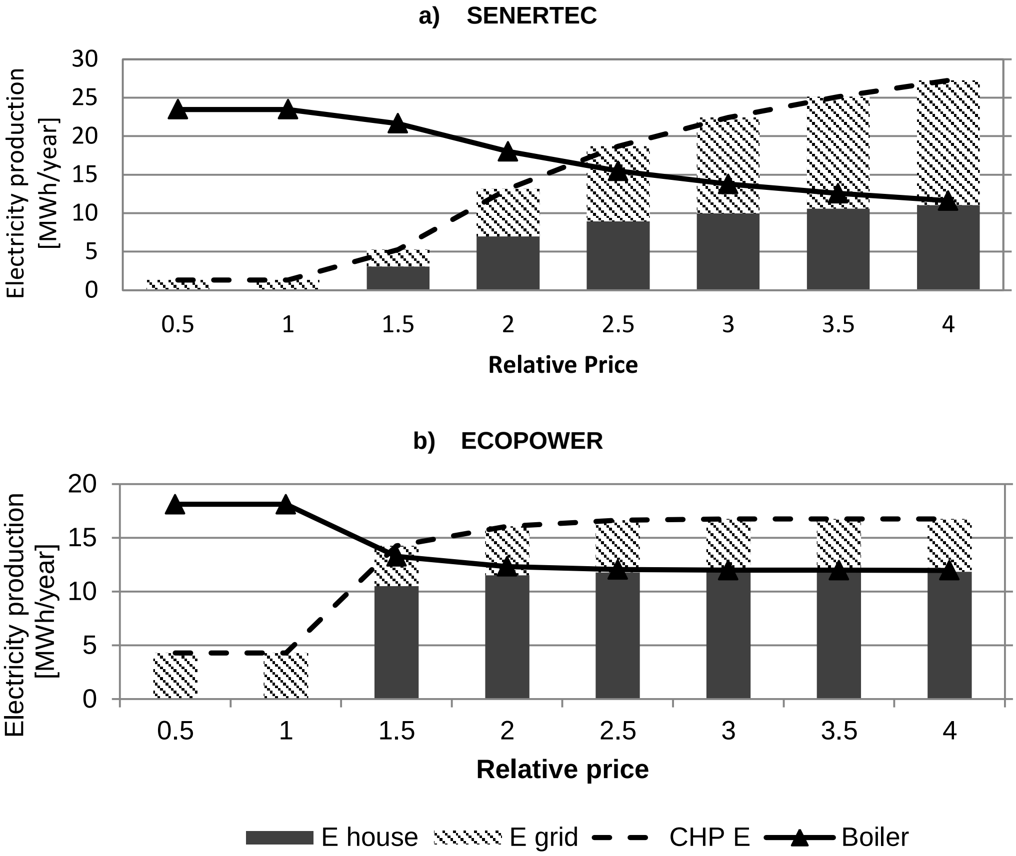

Figure 6: Annual CHP production as a function of the relative price. The dashed line represents the total CHP electricity production. When the local price is lower than the profitable price (RP<1), the electricity generated is sent directly to the grid (striped columns); after that, the CHP production starts to increase while the boiler use (triangle marker) decreases. For both cases RSC = 2.

The jumpy behavior of an electricity generator with linear characteristics such as the modulating micro-CHP was already mentioned in [15]. This situation is due to the fact that under economic optimization a modulating micro-CHP will try to follow the electricity demand [16]. As the spot price remains unchanged, the CHP continues to produce the same amount that was fed into the grid (when RP was lower than 1.5) and additionally tries to meet the local demand (dark shaded part). Producing more electricity is non-optimal from an economic point of view even when the local price increases.

In contrast, the production of a non-modulating micro-CHP is highly dependent on the electricity price. An increase of the electricity price can make the operation of the CHP economically interesting even at moments when the local electricity demand is low. Therefore, increasing the relative price produces also an increase in electricity fed into the grid. Note that it is assumed this electric power is balanced elsewhere in the grid.

Finally, it is important to highlight the evident reduction of the boiler use (line with triangle markers) due to the increase of the thermal production of the CHP in both cases.

4.3. Impact of the VPP on the CHP production

As mentioned before, three different scenarios were studied: a first reference scenario (NO VPP) where there is no cooperation between both houses, a second scenario where the PV installation produces 50% of the annual electric demand of the house first house (50% PV) and a third one where the installation is designed to meet 100 % of the annual electric demand (100% PV).

First, the change of the electricity generation between the first and second scenario is analyzed. In general, when working in the VPP mode, the micro-CHP annual production increases by approximately 6%. Figure 7 illustrates the monthly and daily net change of CHP production (gray columns) from the 'NO VPP' to the '50% PV' scenario for a non-modulating micro-CHP (the modulating micro-CHP gives similar results).

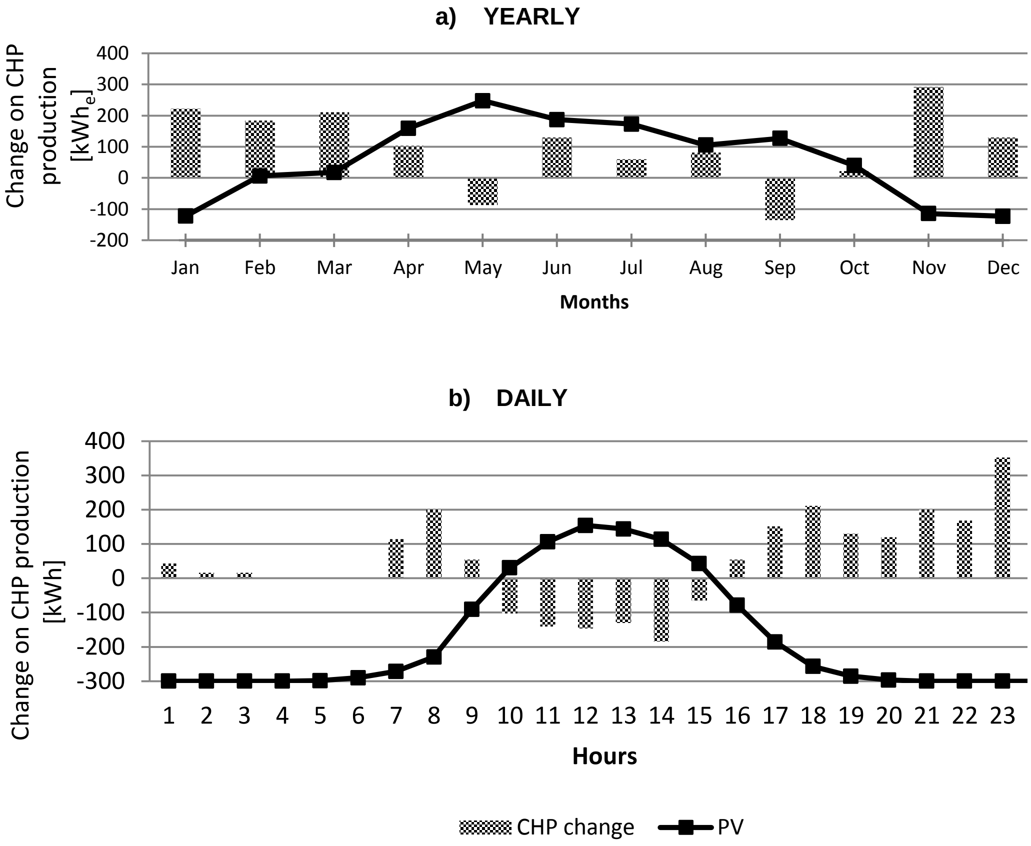

Figure 7: Monthly and daily change of CHP electricity production for 50%PV scenario compared to NO VPP. High increase is visible when PV production (black line) is low. A decrease in the micro-CHP generation is present in summer and during the day (negative blocks).

In order to estimate the monthly and daily change, the total production of the CHP for an entire year at a certain hour (or month) is summed for each scenario. The difference between both scenarios is the change on CHP production shown in Figure 7 .The average PV production (black line) is also presented in the graph.

The upper panel of Figure 7 represents the monthly change of CHP generation. This graph demonstrates that during the summer months the micro-CHP production can decrease (e.g. a reduction of 2.3% results during the month of May) compared to the reference case. The same effect is present during a day (lower panel). At the moment of maximum solar irradiation (e.g., between 10-14 hours) the CHP production drops.

In contrast, during winter and at night when the PV production is low, the CHP generation rises (e.g., an increase of 13% is achieved during the month of November). These facts bear out the complementary nature of both technologies.

On the other hand, it turns out that the electricity production of the micro CHP declines under high PV generation when comparing the reference scenario with the '100 PV' scenario. In this case, a decline of 5% on the micro-CHP production was found instead of a net increase. Similarly as in the previous case, this decrease was more visible in summer and during midday, whereas in winter and at night an increase can be observed.

4.4. Comparison between the three scenarios

The following comparison between the three different scenarios for modulating and non-modulating micro-CHP has been performed. The operational cost of the CHP system is estimated using Equation (1) and listed in Table 2.

Table 2: Operational cost of the CHP system (CHP and auxiliary boiler) for the three different scenarios (NO VPP, 50%PV and 100%PV); comparing both CHP devices. Annual cost expressed in Euros (EUR)

Annual cost/revenue (EUR)	No CHP	No modulation			Modulation		
		NO VPP	50% PV	100% PV	NO VPP	50% PV	100% PV
Cost CHP	-	5120	5400	4864	4280	4463	4198
Cost boiler	8017	4632	4447	4798	4813	4684	4881
Local savings[a]	-	1823	2175	1962	2420	2786	2528
Revenue grid [b]	-	754	712	645	276	221	231
Total cost	8017	7174	6960	7055	6397	6140	6320

[a] The savings due to amount of electricity not bought from the grid but produced by the CHP.

[b]Revenue due to surplus of electricity being fed into the grid.

The table suggests that working in a virtual power plant is (moderately) beneficial for a micro-CHP since it helps to reduce the total operational cost. This statement applies even to the third scenario (although to a minor extent), when the CHP production declines, as explained in the last section (section 4.3). This is due to the fact that although the annual production is reduced, the local use of the electricity produced by the CHP increases and consequently the local savings also rise.

Comparing both CHP devices, it can be concluded that using the modulating micro-CHP results in lower costs for all the scenarios. This is a consequence of the tendency of the modulating micro CHP to follow the electric load as mentioned in section 4.2. In this way, the local energy use is maximized while at the same time the primary energy use is reduced compared to the non-modulating device.

In the following, the revenues due to the PV generation are estimated for the different scenarios. The results are displayed in Table 3. Similar to the case of micro-CHP, the VPP cooperation is positive for the PV owner since the local use of electricity increases and thus the total revenue is higher than that without VPP. Compared to the CHP system, the relative benefit for VPP cooperation is now larger (compare tables 2 and 3).

Table 3: Annual Revenue PV electricity (EUR)

Annual Revenue (EUR)	50% PV		100% PV	
	NO VPP	VPP	NO VPP	VPP
Local savings	281	473	349	732
Revenue grid[a]	52	6	137	45
Total	333	479	486	777

[a]Revenue due to electricity fed into the grid

Furthermore, in order to demonstrate this last statement, a closer look into the distribution of the PV is illustrated in Figure 8. The black part of the column corresponds to the local use of PV and the shaded part represents the percentage of PV electricity that is fed into the grid. The graph shows how the local use of electricity strongly increases with the VPP. For instance, in the case of '50 PV%', the local use rises from 57% ('NO VPP') to 95% (VPP).

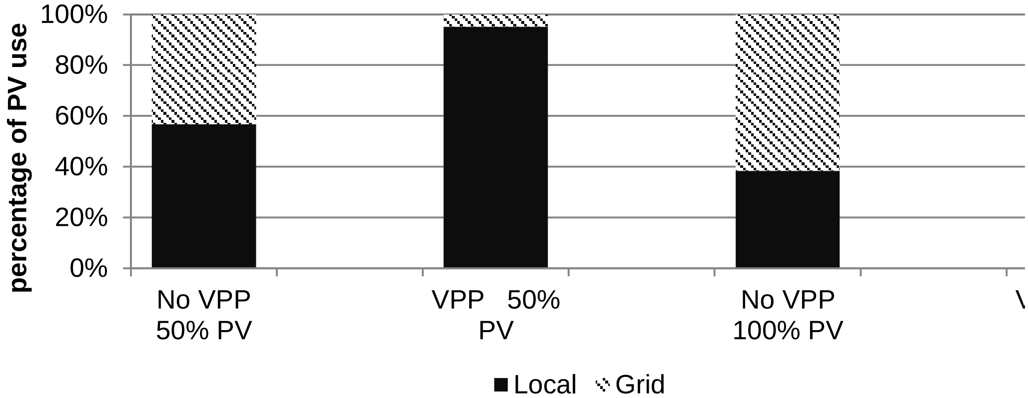

Figure 8: Distribution of PV electricity. The black part of the column corresponds to the percentage of PV electricity that is used locally; the slightly shaded part represents the PV electricity that is fed into the grid. It can be seen that with VPP, the amount of electricity fed into the grid is largely reduced.

Finally, the total cost for energy (heating and electricity) for both houses is calculated using Equation (17). The grid cost corresponds to the part of the electricity that is not generated by the CHP or PV installation and is thus purchased from the grid, as stated in Equation (18). The grid revenue is the income due to the electricity fed into the grid.

$$C_{TOTAL} = G_{grid}(t) - C_{grid}(t) - C_{CHP}(t) - C_{boiler}(t) \quad (17)$$

$$C_{grid}(t) = \left(\dot{E}_{demand}\,(t) - \dot{E}_{local\_chp}(t) - \dot{E}_{local\_PV}(t)\right) \cdot P\ local \quad (18)$$

The results are summarized in Table 4. The boiler cost represents the heating cost for the PV house and was estimated assuming a boiler efficiency of 90%. It is important to take into account that the heat demand of the PV house is lower than that of the CHP house and therefore the cost is relatively low comparing with the aggregated cost of the CHP and boiler.

Nevertheless, assuming that the heat demand of the CHP house is totally met using a condensing boiler with an efficiency of 90%, as shown in Table 2, the resulting operational cost is of 8017€/year. This value is 10% higher than the cost of the CHP system with no VPP and no modulation. Thus, the CHP system leads to a clear advantage for the user even when working without VPP.

From Table 4, it becomes clear that in all cases working in a VPP (and under the assumptions of this work) leads to better economic results for both houses. This is due to the fact that with the VPP the local use of PV and CHP rise largely and thus the savings increase and the grid cost decreases. Furthermore, it is important to highlight that using a modulating micro-CHP leads to lower costs. This fact has been discussed above in the present section (see Table 2) arriving to the conclusion that the modulating micro-CHP makes more optimal use of the primary energy. Finally, it is remarkable that increasing the amount of PV electricity in the system results in a reduction on the CHP electricity generation. This is directly reflected as a decrease in the operational cost of the CHP.

Table 4: Calculation of the aggregated annual energy cost of both houses considering the different scenarios and the two cogeneration devices.

	No modulation				**Modulation**			
Annual energy cost (EUR)	50% PV NO VPP	50% PV VPP	100% PV NO VPP	100% PV VPP	50% PV NO VPP	50% PV VPP	100% PV NO VPP	100% PV VPP
Grid cost	1179[a]	636	1111[a]	589	582.5[b]	25	515[b]	22.6
Operational Cost CHP	5120	5400	5120	4864	4280	4463	4280	4198
Operational Cost Aux. boiler	4632	4447	4632	4798	4813.5	4684.5	4813.5	4881.5
Operational Cost boiler	2102	2102	2102	2102	2102	2102	2102	2102
Grid revenue PV	52	6	137	45	52.4	6	137	45
Grid revenue CHP	755	712.5	755	645	276	221	276	231
Total cost	12226	11866	12073	11663	11449	11047	11297	10927

a,b: Note that between these scenarios (a-a) and (b-b) the main difference is the distribution of the PV electricity between the local area or the grid.

5. CONCLUSIONS

In this work, first the influence of the heat storage buffer in the electricity production of the CHP was studied. It was concluded that there is a significant change on the production from the case where no storage is available. This change is mainly reflected as a large increase of production in summer. In colder seasons the difference is almost negligible.

Furthermore, a comparison of the behavior of the CHP with and without VPP was performed. The results show that in the scenario with 50% PV coverage in one house, the electricity generation of the CHP in the other house increases, especially in winter and summer. On the other hand, in the 100% PV-coverage scenario a total reduction of the electricity generation is found. This suggests that with high penetration of PV the CHP production will be affected.

Furthermore, it was shown that the decrease of the CHP production (e.g., 100% of PV scenario with VPP) does not lead to any economic disadvantage. On the contrary, working in cooperation is always beneficial. This is due to the fact that the rate of local consumption increases. Therefore, the prosumer receives more advantageous prices for the electricity produced.

It is also remarkable that when both micro-CHP devices are compared, the ability to modulate results in an economical advantage. Moreover, it was seen that contrary to the traditional heat lead control, the economic optimization behaves more similar to electric lead control trying to follow the electric demand of the house. This is possible thanks to the use of the storage tank which, as seen before helps to increase the annual CHP production and to produce electricity at moments of low heat demand.

In summary, it can be concluded that working in a VPP increases the amount of local consumption decreasing the burdens imposed to the electric grid and giving clear advantages to the prosumers. Further research will aim to generalize these conclusions to the case of small neighborhoods and different renewable technologies.

Finally, it should be mentioned that all conclusions above are subject to the assumptions made and explained in this paper.

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